

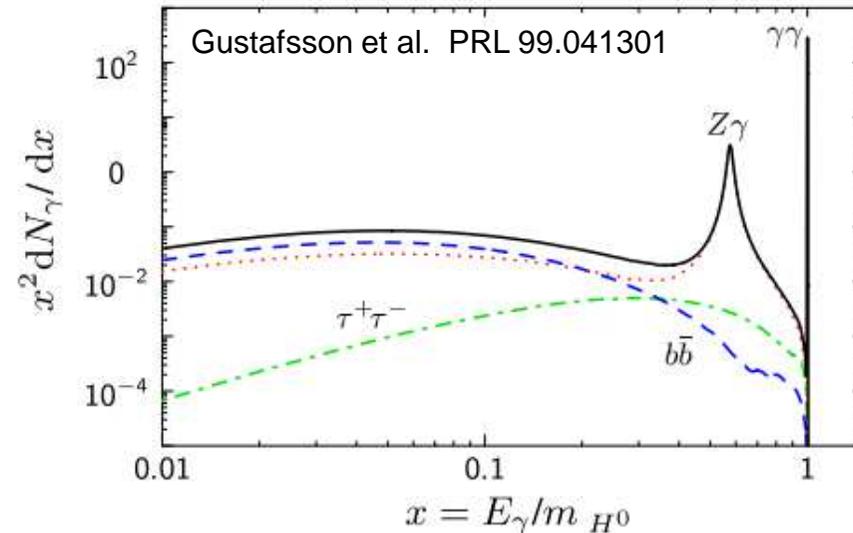
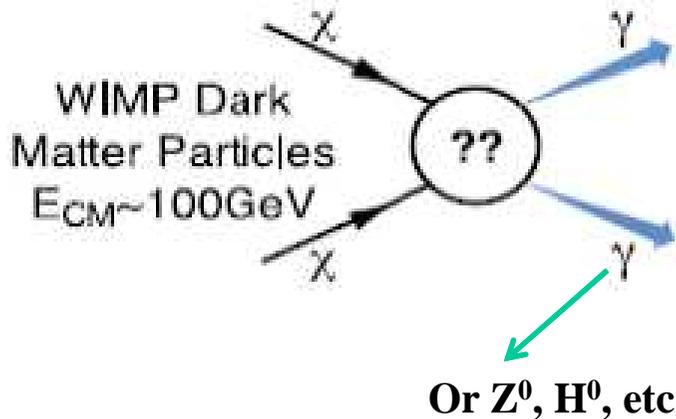
Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

Andrea Albert (SLAC)
On Behalf of the Fermi-LAT
Collaboration
DPF 2013 at UC Santa Cruz
August 16th, 2013

Spectral Lines from WIMPs

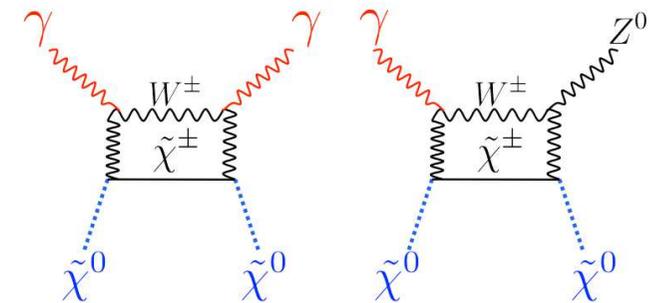


Spectral Line



- **WIMP = Weakly Interacting Massive Particle**

- DM candidate (e.g. neutralino)
- Believe the Milky Way sits in a large spherical “halo” or cloud of DM
 - **Non-relativistic (cold) DM**



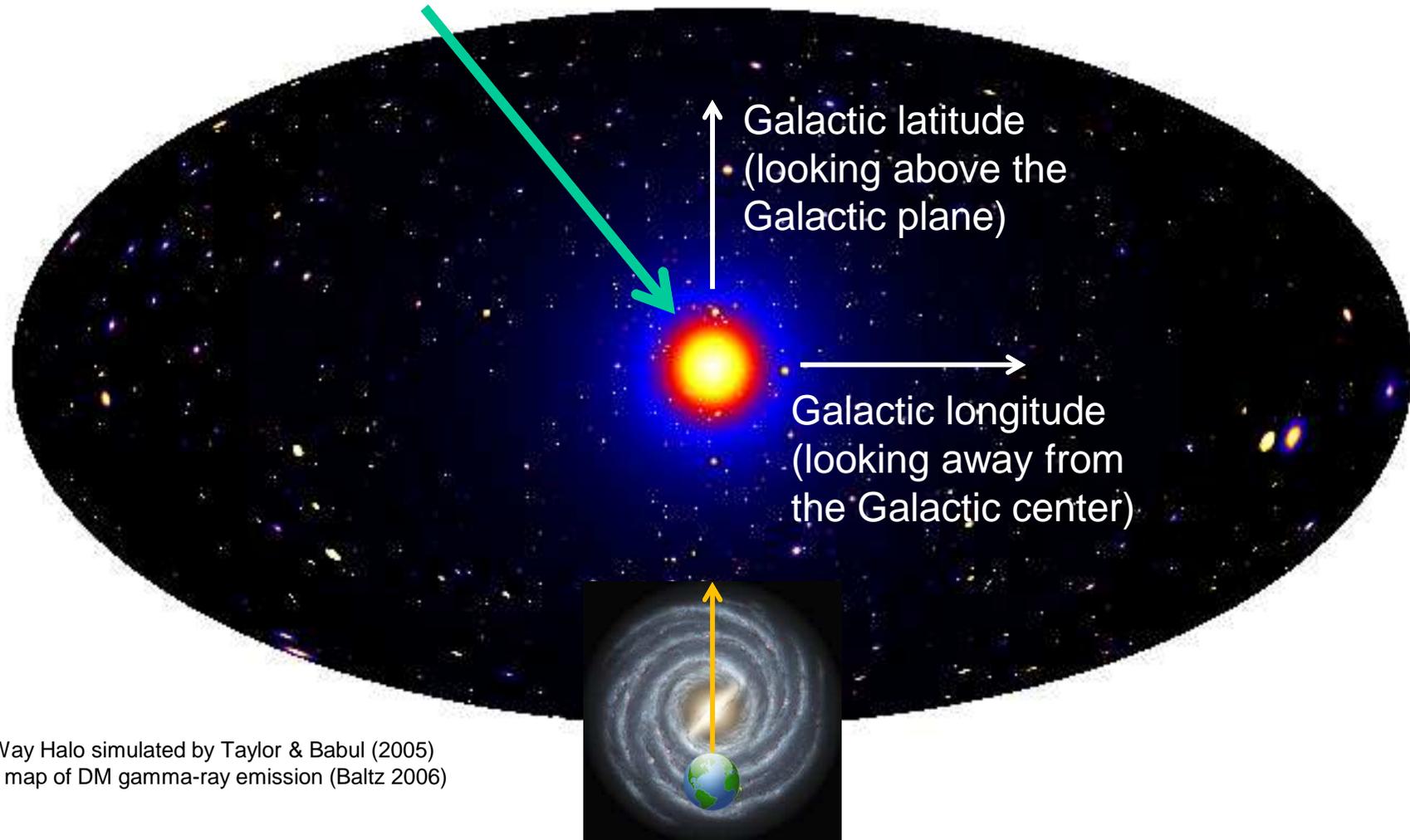
- $\chi\chi \rightarrow \gamma X$ ($X = \gamma, Z, H$) gives monochromatic signal

- Advantage: sharp, distinct feature (WIMP “smoking gun”)
- Disadvantage: low predicted counts (loop suppressed)

Expected Galactic DM γ -ray signal

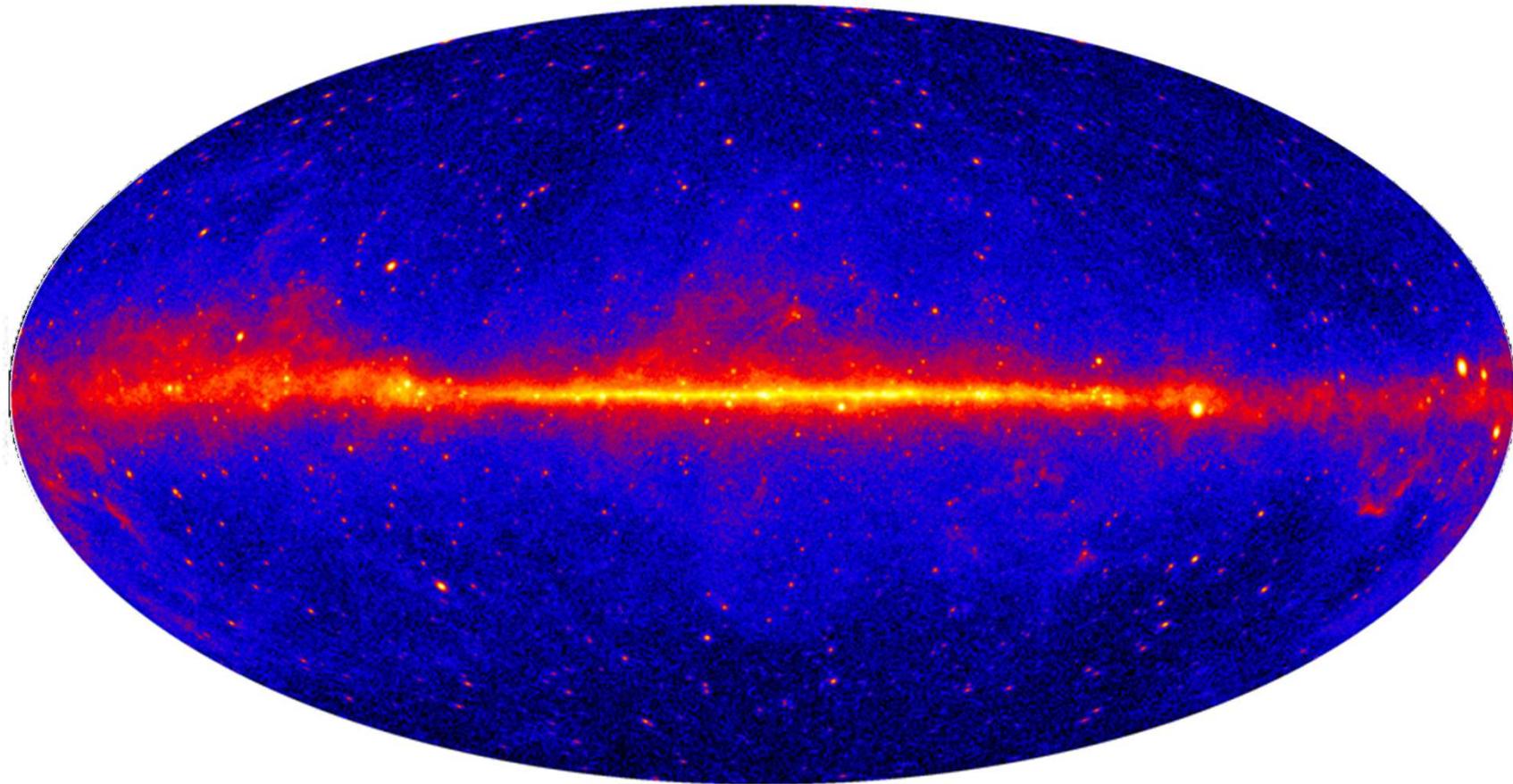


Smooth component peaked in Galactic Center
(central cuspiness has large uncertainties)



Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)

Large Astrophysical Background



Milky Way Halo simulated by Taylor & Babul (2005)
All-sky map of DM gamma-ray emission (Baltz 2006)



Public Data Release:

All γ -ray data made public within 24 hours (usually less)

Si-Strip Tracker:

convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:

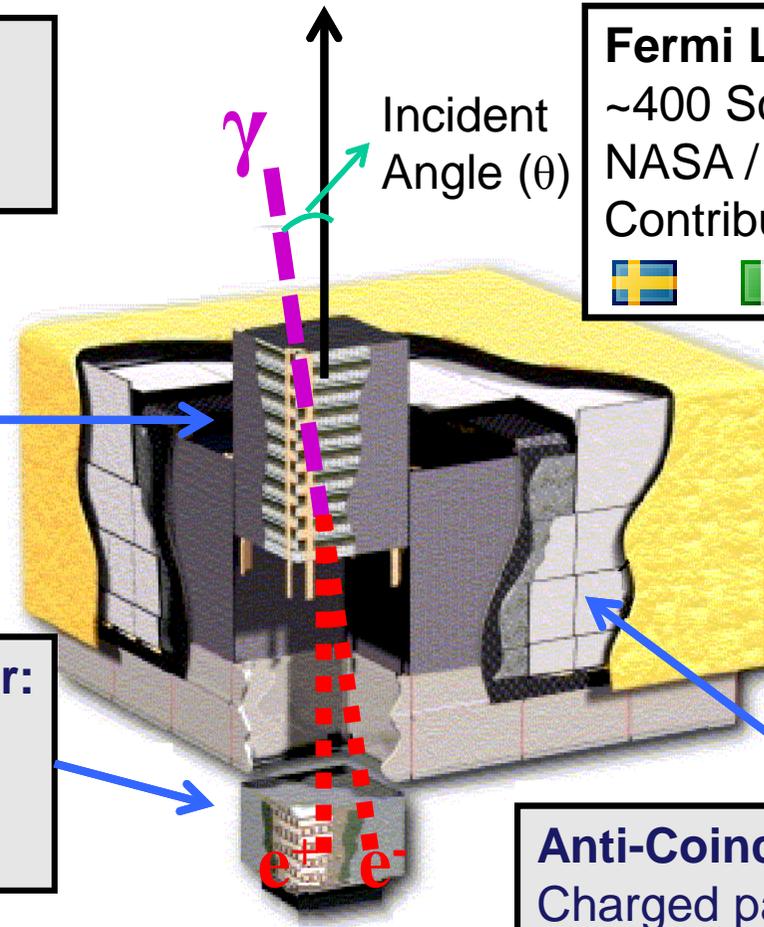
measure γ energy
image EM shower
EM v. hadron separation

Trigger and Filter:

Reduce data rate from $\sim 10\text{kHz}$ to $300\text{-}500\text{ Hz}$

Fermi LAT Collaboration:

~ 400 Scientific Members,
NASA / DOE & International Contributions



Anti-Coincidence Detector:

Charged particle separation

En Range and Coverage:

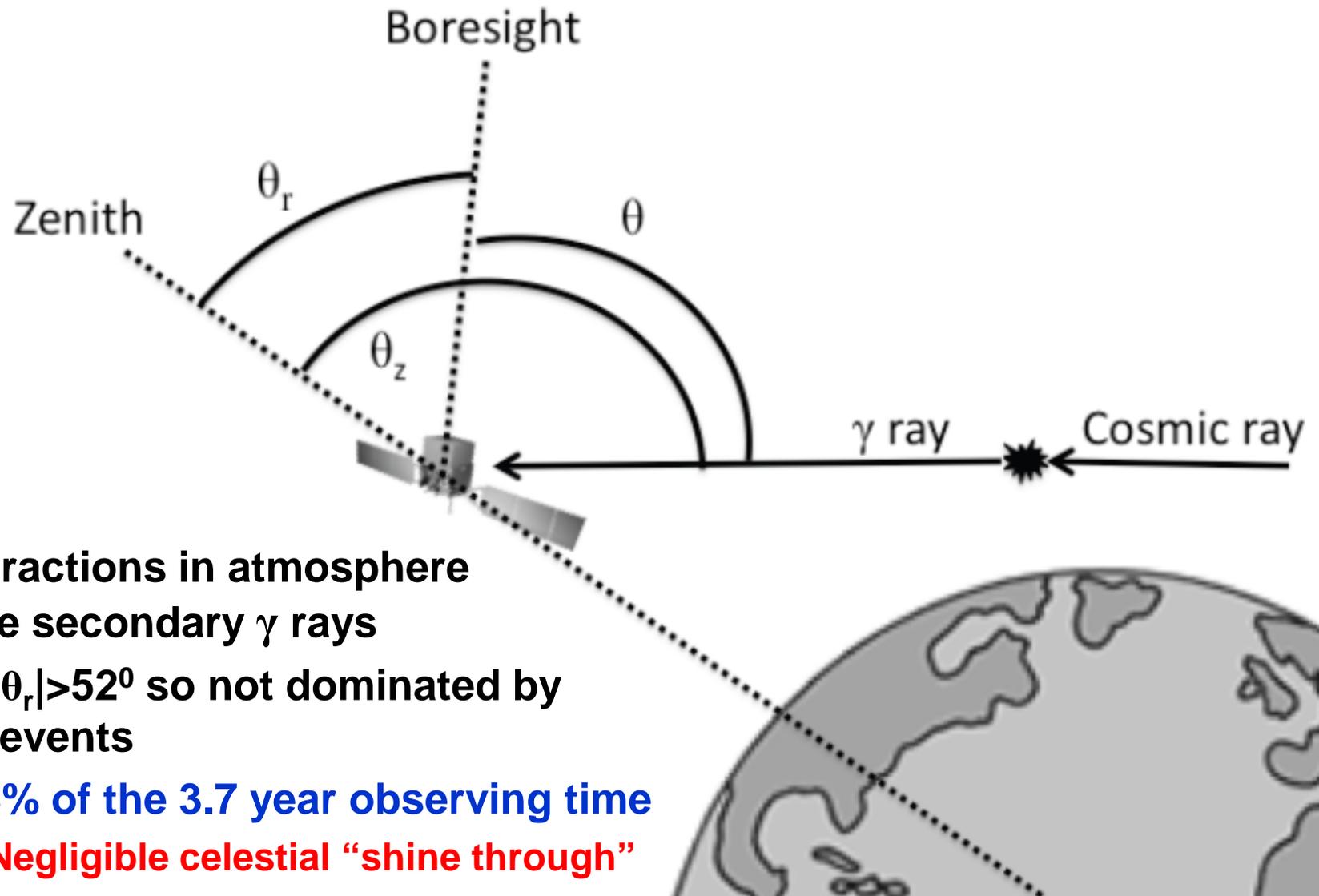
20 MeV to $>300\text{ GeV}$
See whole sky every 3 hrs



TABLE I. Summary table of data selections.

Parameter	Galactic data	Limb data
Observation Period	2008 August 4 – 2012 April 4	2008 August 4 – 2012 October 6
Mission Elapsed Time (s)	[239557447, 356434906]	[239557447, 371176784]
Energy range (GeV)	[2.6, 541]	[2.6, 541]
Zenith cut ($^{\circ}$)	$\theta_z < 100$	$111 < \theta_z < 113$
Rocking angle cut ($^{\circ}$) ^a	$ \theta_r < 52$	$ \theta_r > 52$
Data quality cut ^b	Yes	Yes
Source masking (see text)	Yes	No

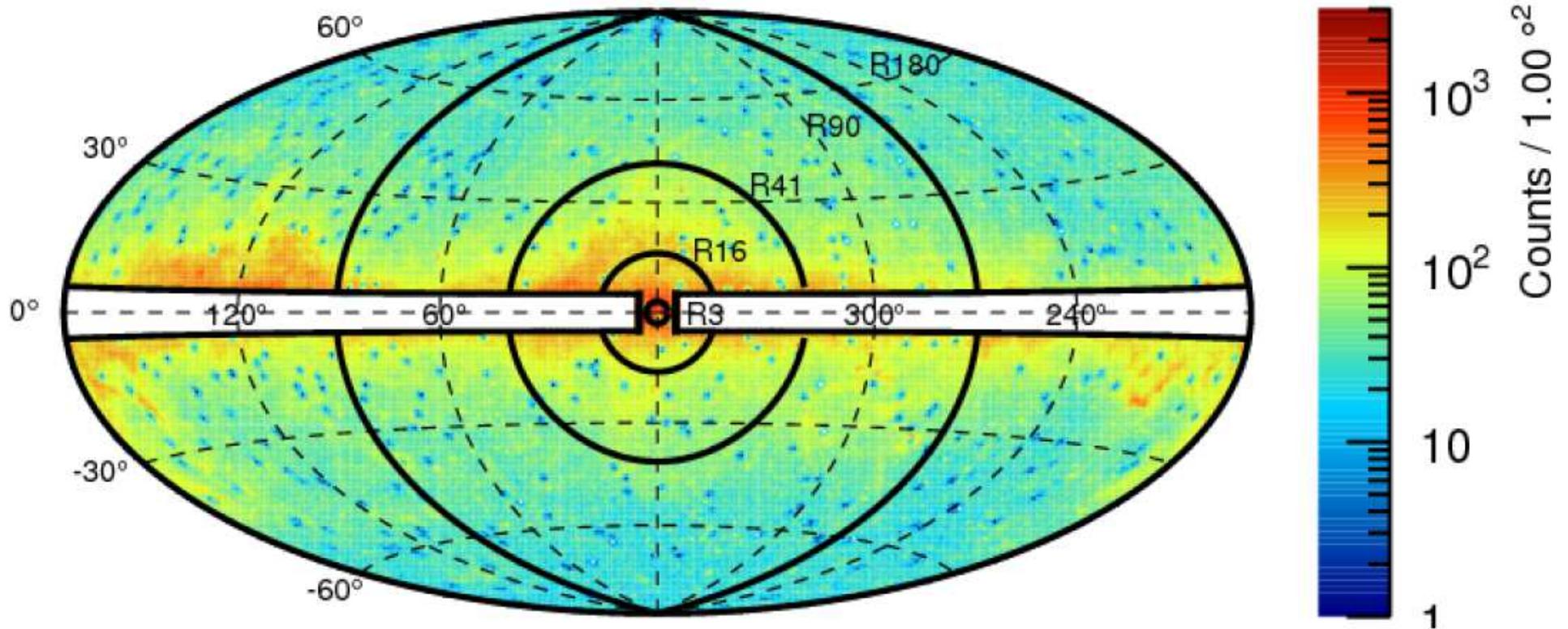
- **Search for lines from 5 – 300 GeV using 3.7 years of data**
- **Use P7REP_CLEAN event selection**
 - **Reprocessed data with updated calorimeter calibration constants**
 - **Clean cuts are recommended for faint diffuse emission analysis**
- **Mask bright ($>10\sigma$ for $E > 1$ GeV) 2FGL sources**



- CR interactions in atmosphere produce secondary γ rays
- Select $|\theta_r| > 52^\circ$ so not dominated by large θ events
 - 0.03% of the 3.7 year observing time
 - Negligible celestial “shine through”



3.7 year Counts Map



R3 (contracted NFW, no src masking)
R16 (Einasto)
R41 (NFW)

R90 (Isothermal)
R180 (DM Decay)

Fitting Method



Predicted Spectrum

Signal Model

Background Model

$$C(E', P_E | \vec{\alpha}) = n_{\text{sig}} D_{\text{eff}}(E', P_E | E_\gamma) w_{\text{sig}}(P_E) + \frac{n_{\text{bkg}}}{c_{\text{bkg}}} \left(\frac{E'}{E_0} \right)^{-\Gamma_{\text{bkg}}} \eta(E') w_{\text{bkg}}(P_E)$$

$$D_{\text{eff}}(E'; E_\gamma) = \int^{\text{FoV}} \int^{\text{ROI}} D(E'; \theta | E_\gamma) \frac{I_{\text{sig}}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\text{sig}}} d\Omega d\Omega_{\hat{v}}$$

Effective Energy Dispersion

Incorporates energy reconstruction quality (P_E)

$$\eta(E') = \int^{\text{FoV}} \int^{\text{ROI}} \frac{I_{\text{bkg}}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\text{bkg}}} d\Omega d\Omega_{\hat{v}}$$

Effective Area Corrections

- **Maximum likelihood fit at E_γ in sliding energy window ($\pm 6\sigma_E$)**
 - **Fit from 5 to 300 GeV**
 - **$0.5\sigma_E$ steps (88 fit energies)**
- n_{sig} , n_{bkg} , Γ_{bkg} free in fit
- c_{bkg} is given by normalization of background model
- Include P_E distributions for signal and background: $w(P_E)$
 - **Take from data for each fit (entire ROI and energy fit window)**

Systematic Effects in each ROI



- **Uncertainties that affect the conversion from n_{sig} to $\Phi_{\gamma\gamma}$**
 - E.g., exposure uncertainties
 - Do not affect fit significance
- **Uncertainties that scale n_{sig}**
 - E.g., modeling energy dispersion
 - Affect significance, but will not induce false signals

Quantity	Energy	R3	R16	R41	R90	R180
$\left\{ \begin{array}{l} \delta\epsilon/\epsilon \\ \delta\epsilon/\epsilon \end{array} \right.$	5 GeV	0.10	0.10	0.11	0.12	0.14
	300 GeV	0.10	0.10	0.12	0.13	0.16
$\left\{ \delta n_{sig}/n_{sig} \right.$	All	± 0.07 ± 0.12				
$\left\{ \begin{array}{l} \delta f \\ \delta f \\ \delta f \end{array} \right.$	5 GeV	0.020	0.020	0.008	0.008	0.008
	50 GeV	0.024	0.024	0.015	0.015	0.015
	300 GeV	0.032	0.032	0.035	0.035	0.035

$$TS = 2 \ln \frac{\mathcal{L}(n_{sig} = n_{sig,best})}{\mathcal{L}(n_{sig} = 0)} \quad s_{local} = \sqrt{TS}$$

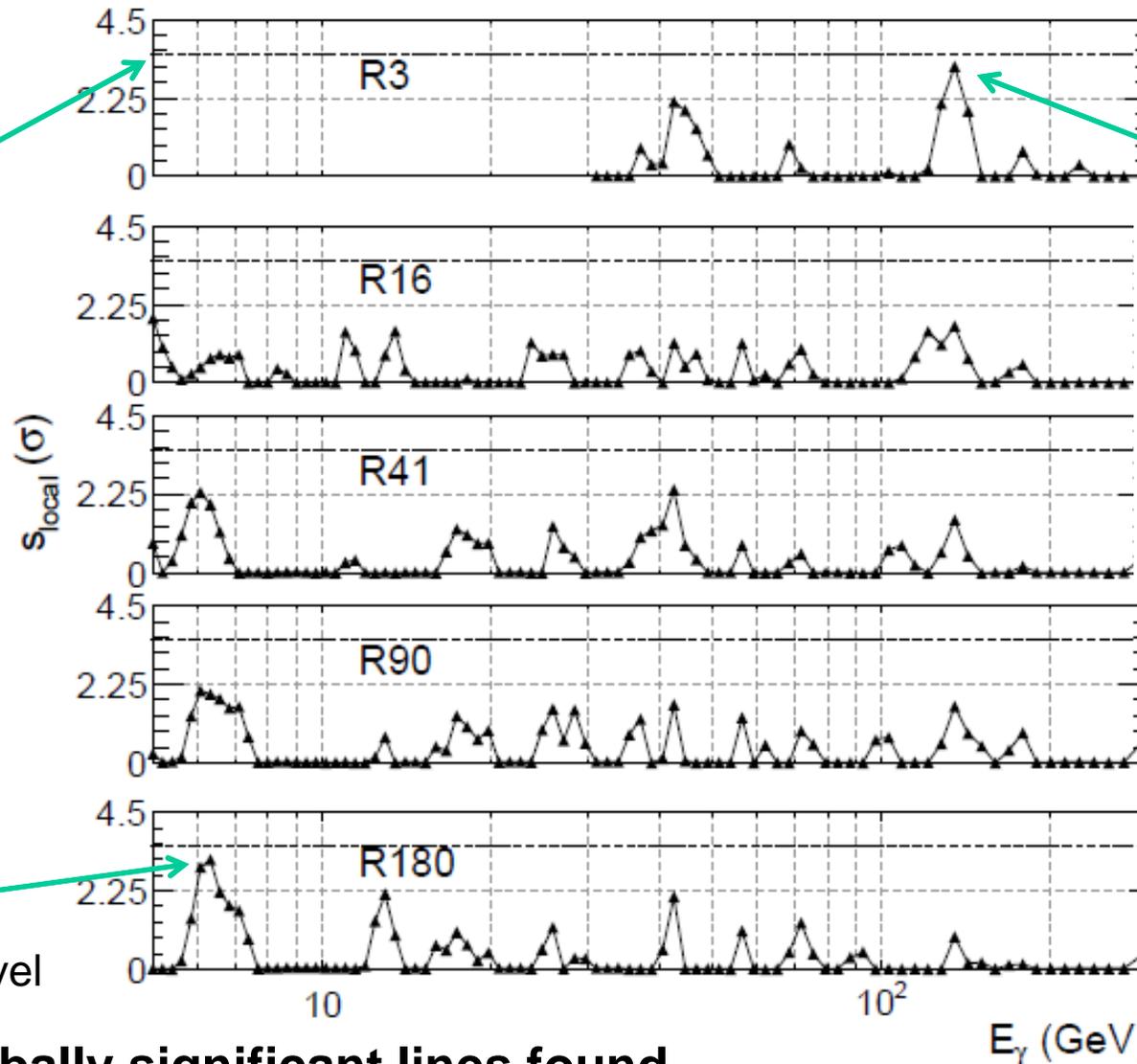
- **Uncertainties that induce or mask a signal**
 - Express as uncertainty in fractional signal, δf

$$f = \frac{n_{sig}}{b_{eff}} \simeq \frac{s_{local}^2}{n_{sig}}$$

Fitting Results



$S_{\text{global}} = 2\sigma$



$E_\gamma = 135 \text{ GeV}$

$S_{\text{local}} = 3.2\sigma$

$S_{\text{global}} = 1.5\sigma$

$f = 0.58$

Much larger than
systematic level

$E_\gamma = 6 \text{ GeV}$

$S_{\text{local}} = 3.1\sigma$

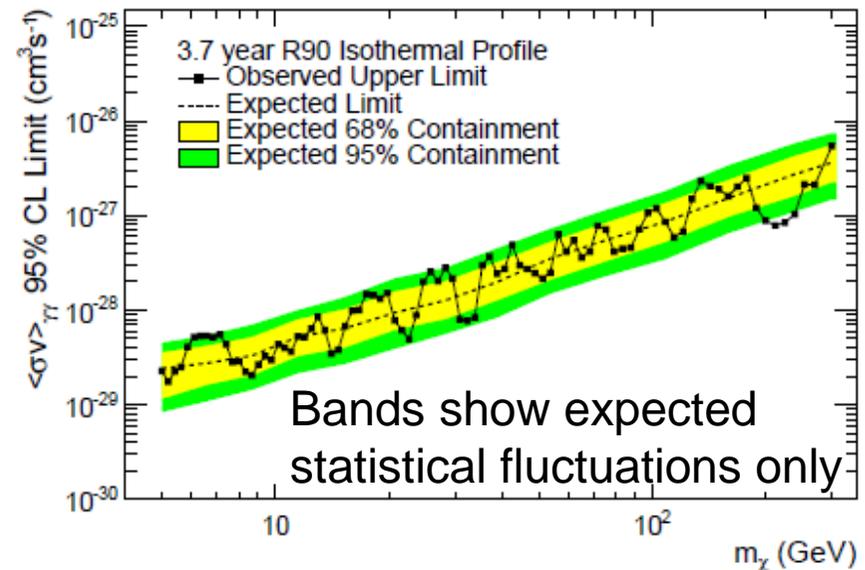
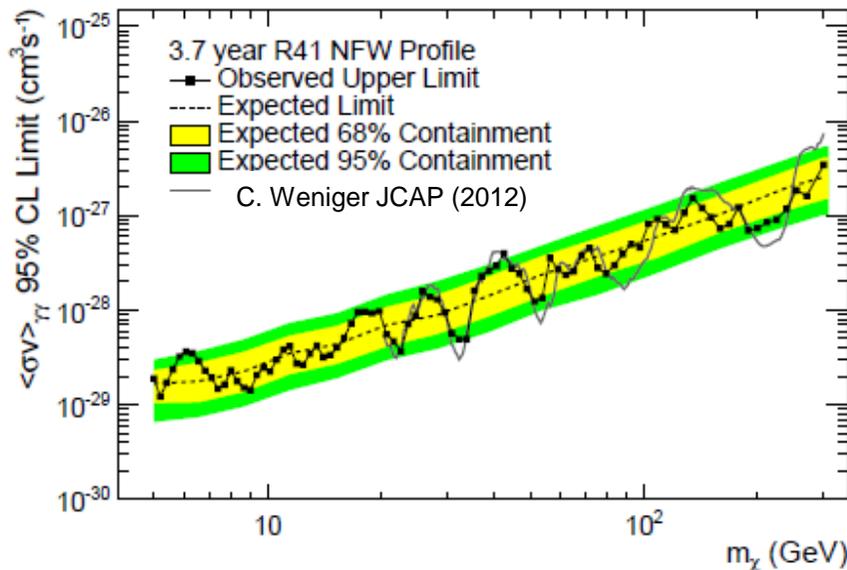
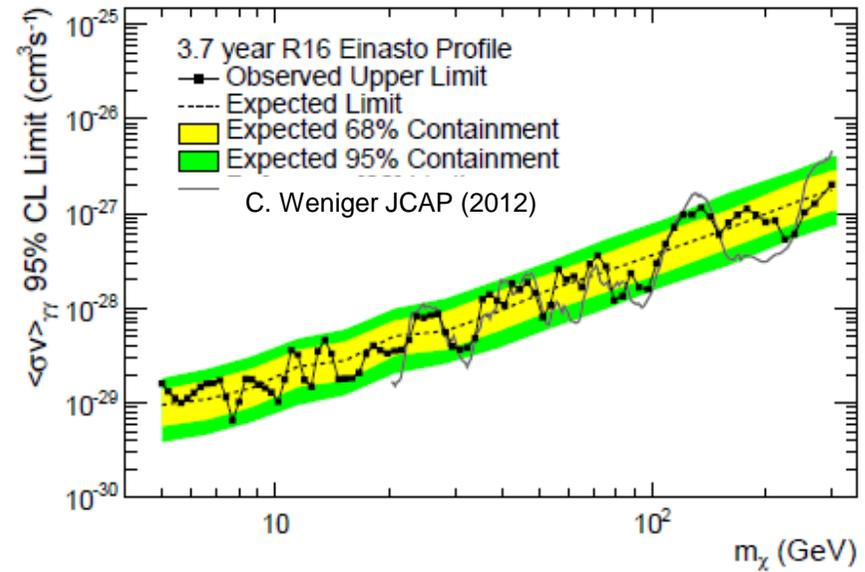
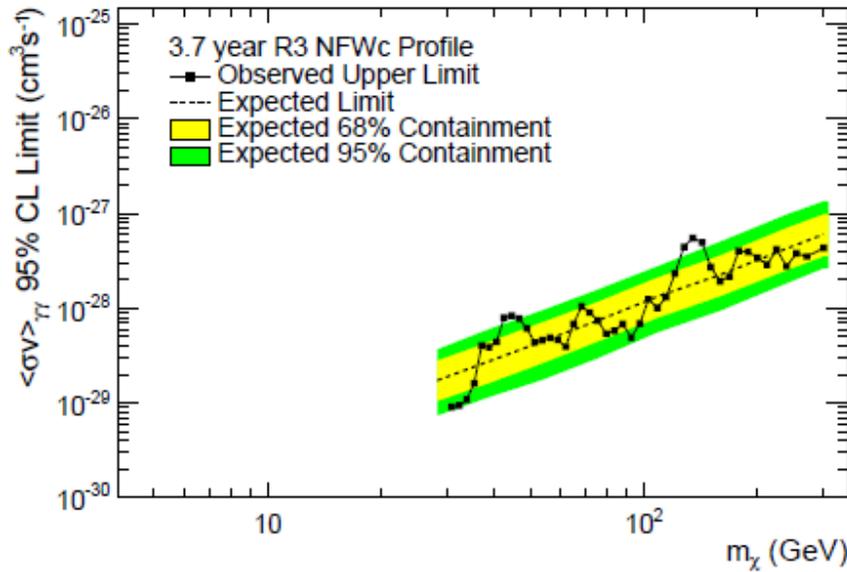
$S_{\text{global}} = 1.4\sigma$

$f = 0.01$

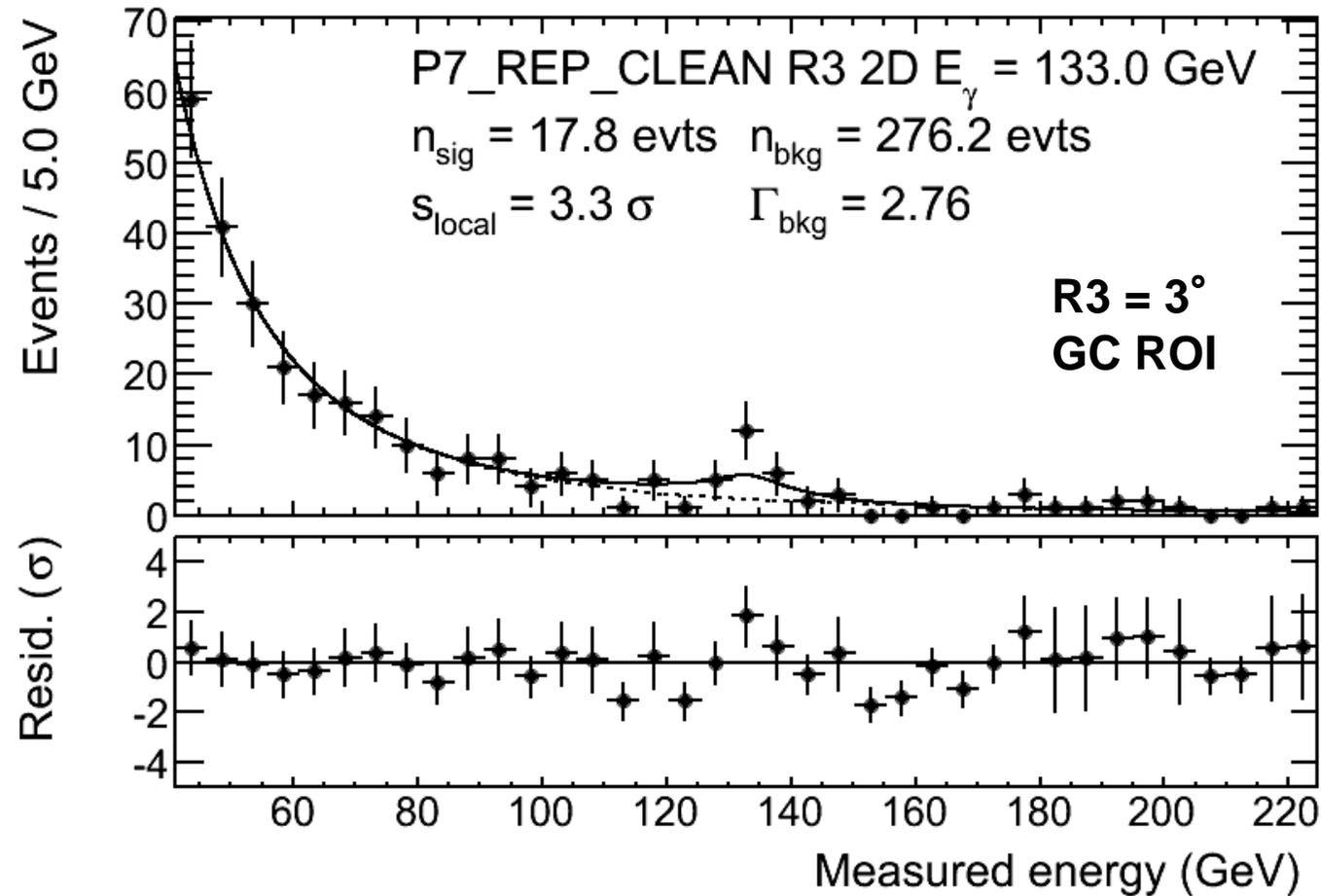
At systematic level

- **No globally significant lines found**

95% CL $\langle\sigma v\rangle$ upper limits

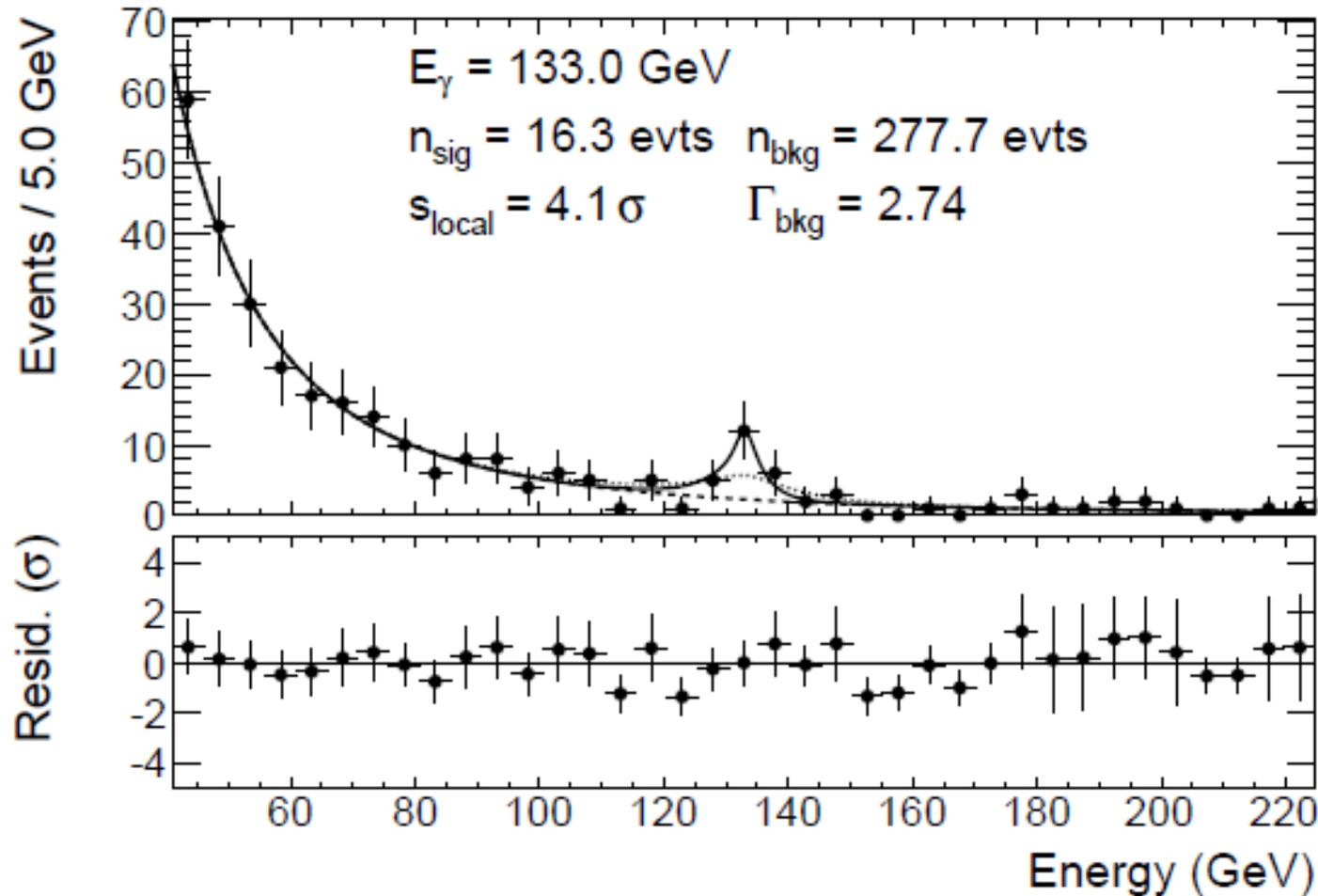


The Line-like Feature near 133 GeV



- **3.2 σ (local) 2D fit at 133 GeV with reprocessed data**
 - **Fit with energy dispersion model that includes event-by-event energy recon. quality estimator P_E (“2D” model)**
 - **Expected 2D signal model to increase signif. of signals by ~15%**

Width of 133 GeV Feature

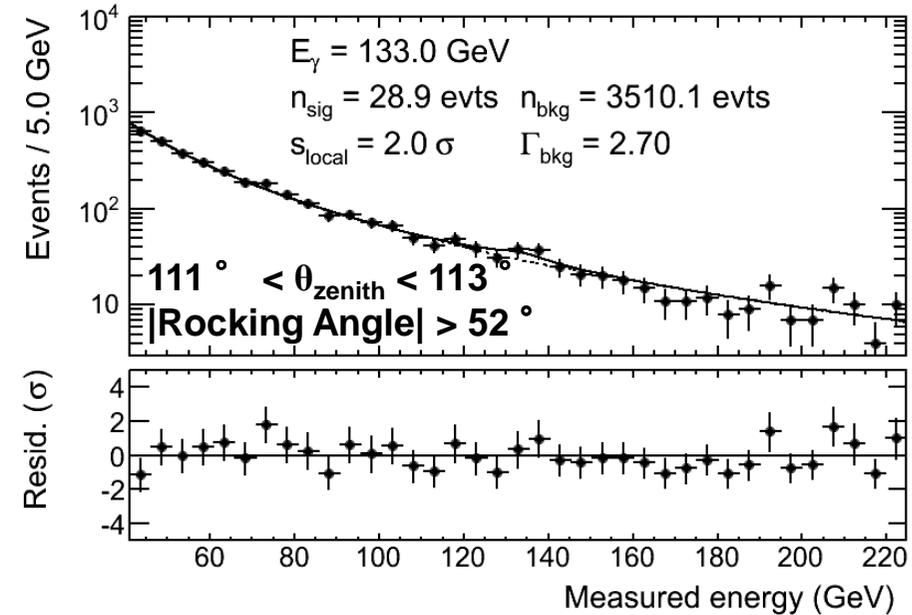
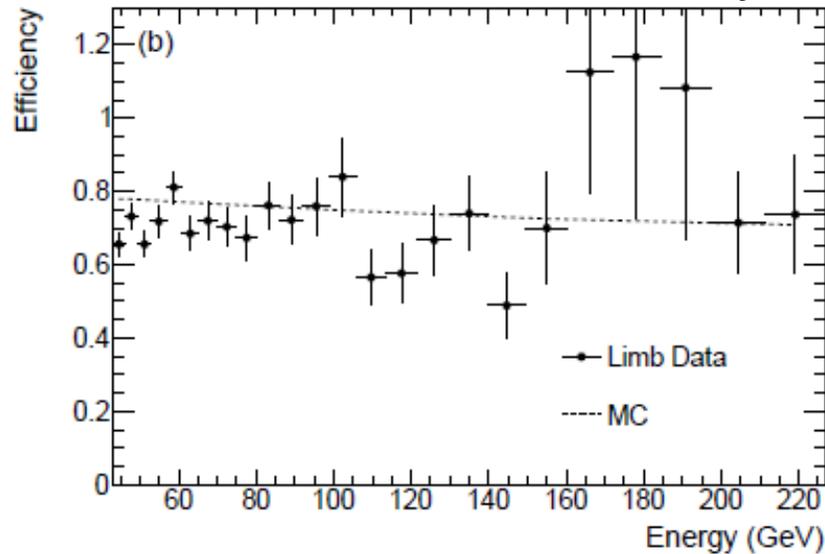


- Let width scale factor float in fit (while preserving shape)
- $s_\sigma = 0.32^{+0.11}_{-0.07}$ $\Delta\text{TS} = 9.4$
 - Feature in data is much narrower than expected energy resolution ($s_\sigma=1$)

133 GeV in the Earth Limb spectrum

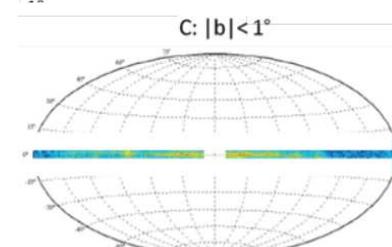
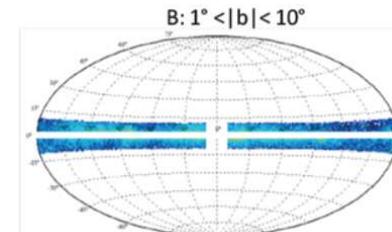
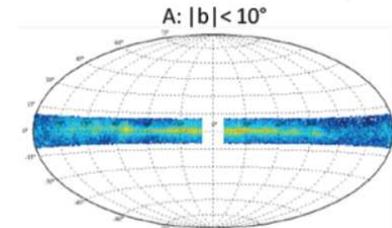
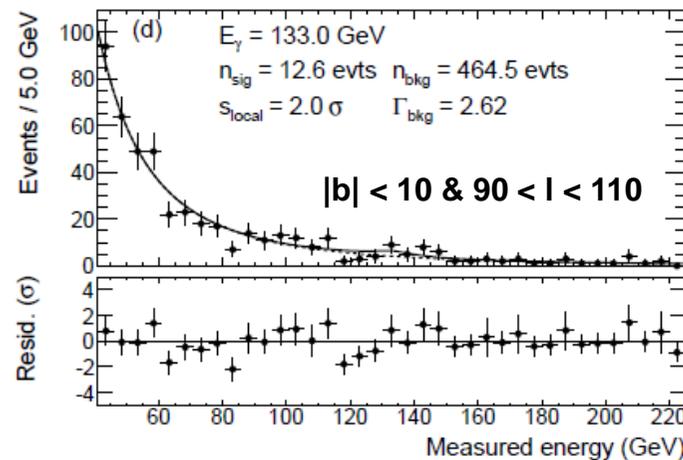
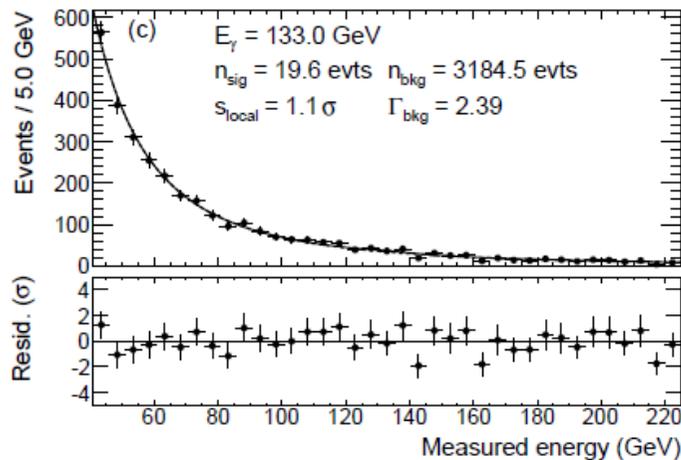
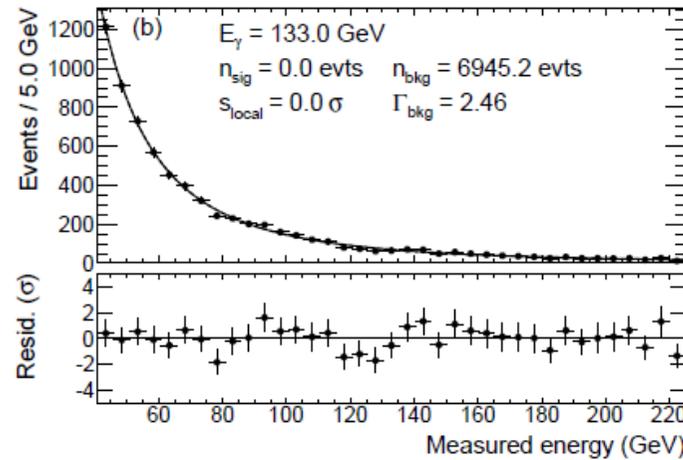
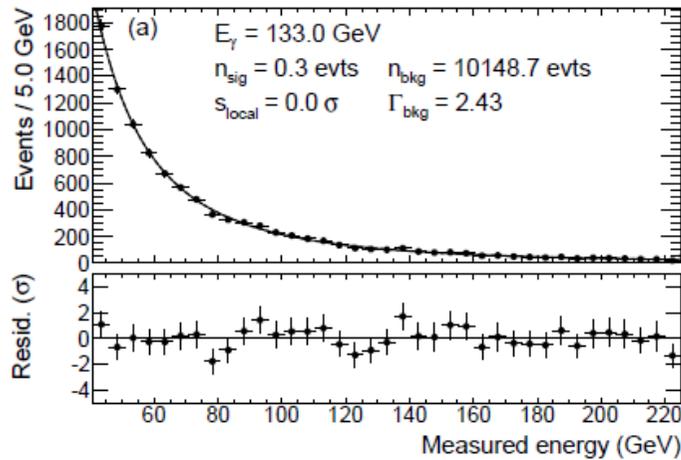


P7Transient to P7Clean Efficiency



- **Line-like feature in the limb at 133 GeV (2.0σ local signif)**
 - Appears when LAT is pointing at the Limb ($|\theta_r| < 52^\circ$)
 - Surprising since limb should be smooth power-law
 - $S/N_{\text{limb}} \sim 14\%$, while $S/N_{R3} 61\%$
 - **Limb feature not large enough to explain all the GC signal**
- **Dips in efficiency (less stringent Transient cuts -> Clean cuts) below and above 133 GeV**
 - Appear to be related to CAL-TKR event direction agreement
 - Could be artificially sculpting the energy spectrum

133 Feature in the inverse ROIs



E. Bloom Fermi Symposium 2012

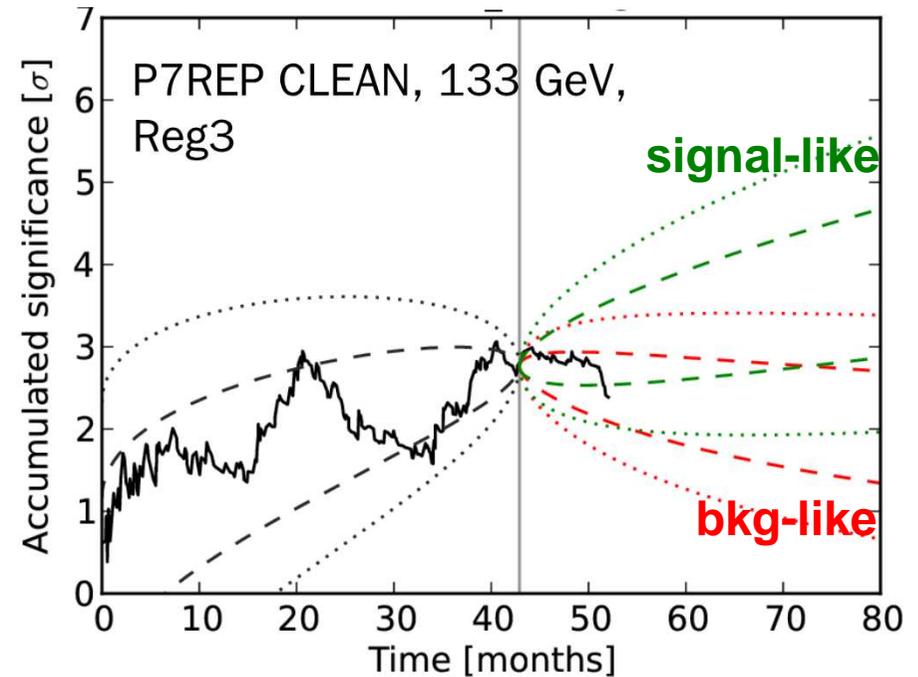
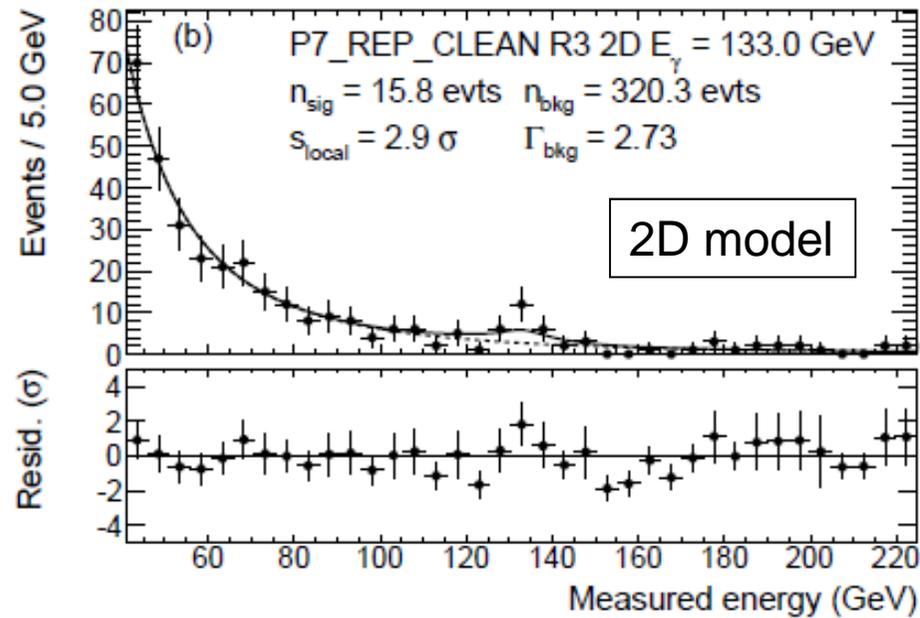
- No obvious feature at 133 GeV in the inverse ROIs

133 GeV Feature in 4.4 year dataset



Weniger et al (2013)

<http://fermi.gsfc.nasa.gov/ssc/proposal/s/alt_obs/white_papers_eval.html>



- s_{local} decreased in 4.4 yr data by $\sim 10\%$ compared to 3.7 yr data
- Since spring 2012, feature has decrease
– More “background-like”

Summary



- **Search for spectral lines from 5--300 GeV in 5 ROIs**
 - Use 3.7 year P7_REP_CLEAN dataset
 - Submitted for publication in PRD (<http://arxiv.org/abs/1305.5597>)
- **No globally significant lines detected**
 - All below 2σ global significance
 - Have set 95% CL $\Phi_{\gamma\gamma}$, $\langle\sigma v\rangle_{\gamma\gamma}$, and $\tau_{\gamma\gamma}$ limits
- **See a narrow residual near 133 GeV in the GC**
 - Not (completely) an obvious systematic error
 - Larger than expected systematic uncertainty
 - Feature in Limb is smaller than GC feature
 - Feature does not appear in inverse ROI
 - Bkg fluctuation?
 - Much narrower than expected energy resolution
 - Decreasing with more data
- **More data and study will improve future line analyses**
 - Pass 8 \rightarrow ~25% increase in A_{eff}
 - More Limb data from pole stares and future ToOs

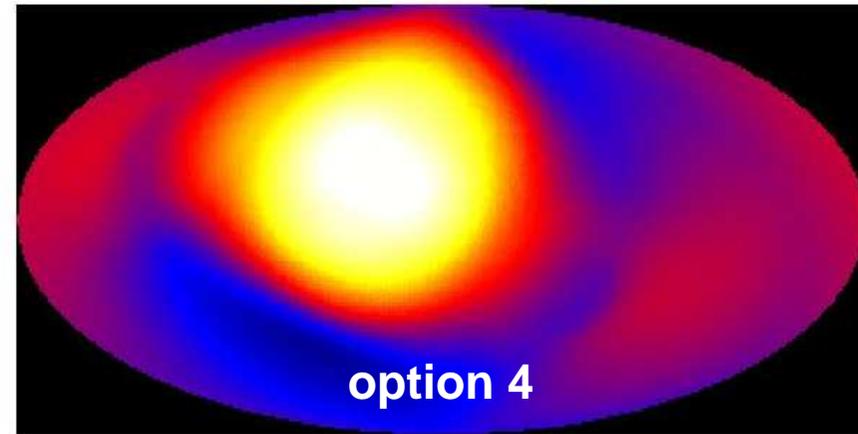
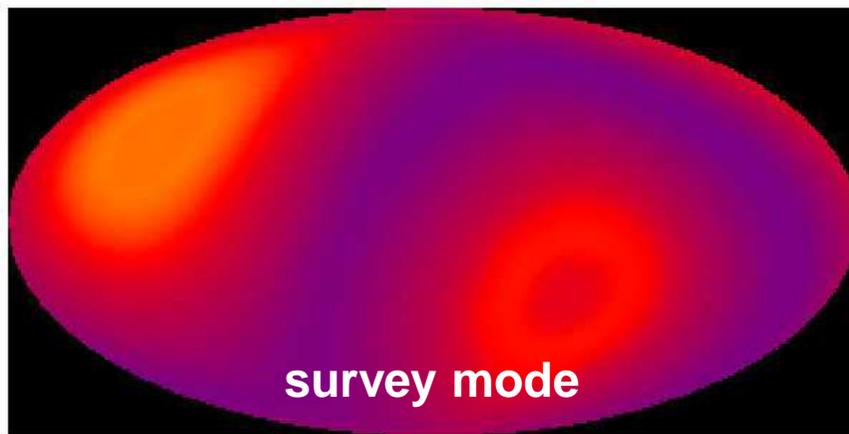


BACKUP SLIDES

Modified Observing Strategy



- more info can be found on FSSC
<http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html>
- Panel discussed white paper proposals July 25th and recommended a switch to “option 4” around December 2013.
 - Option 4 points to keep the GC in the field of view, while still providing relatively uniform all-sky coverage



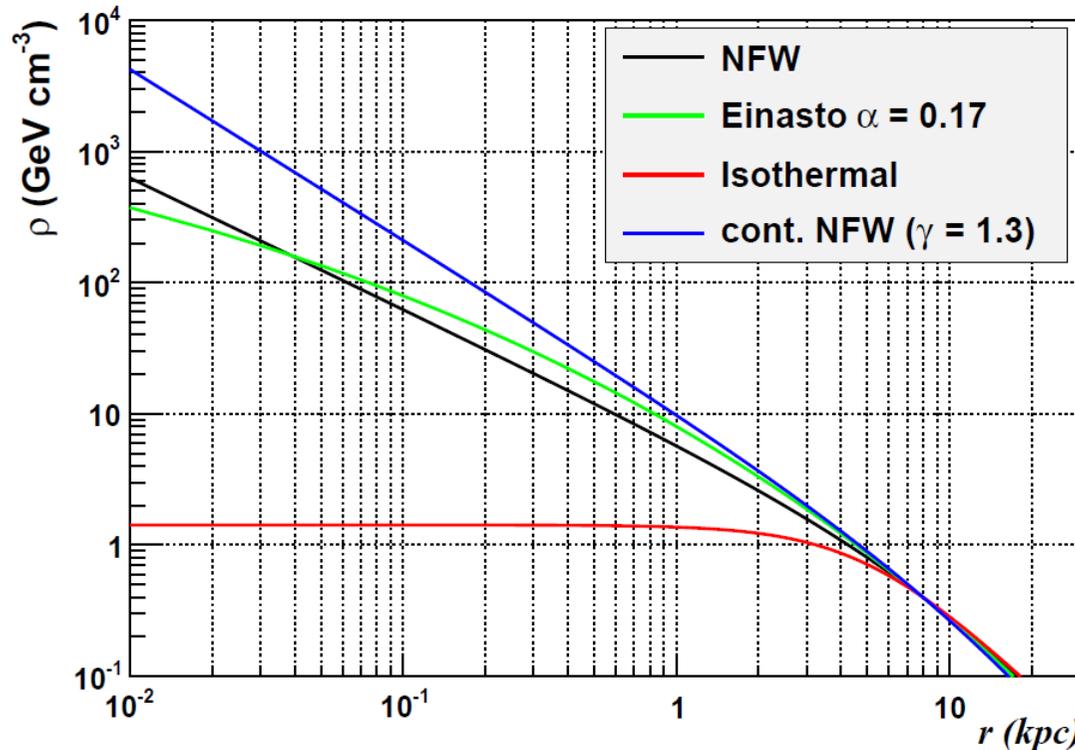
exposure maps

Indirect WIMP Signatures (2)



Astrophysics

$$\Phi_\chi(E, \psi) = \frac{\langle \sigma_\chi v \rangle}{2} \sum_f \frac{dN_f}{dE} B_f \int_{LOS} dl(\psi) \frac{1}{4\pi} \frac{\rho(l)^2}{m_\chi^2}$$



J-factor – Line of sight integral over a ROI

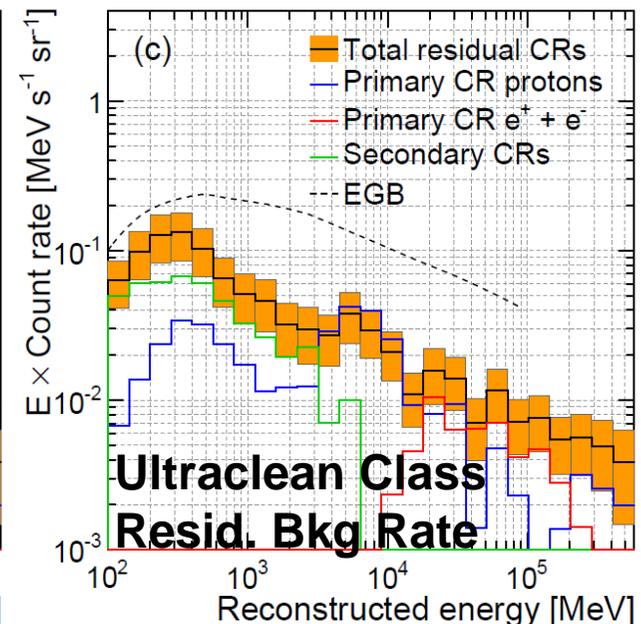
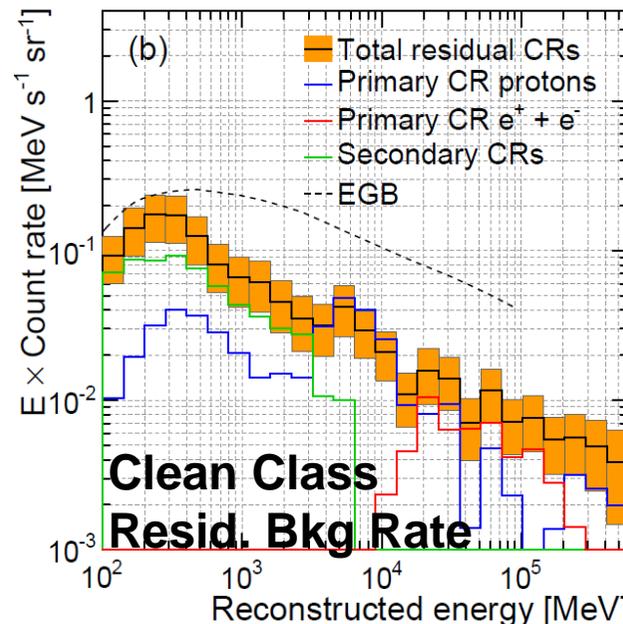
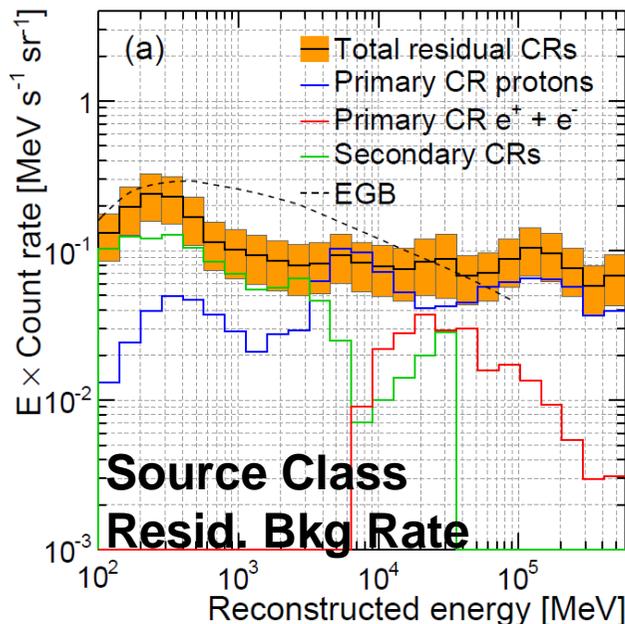
Various models for the smooth DM density as a function of distance from Galactic center (r)
Derived from fits to N-body simulations

Gamma-ray Event Classes



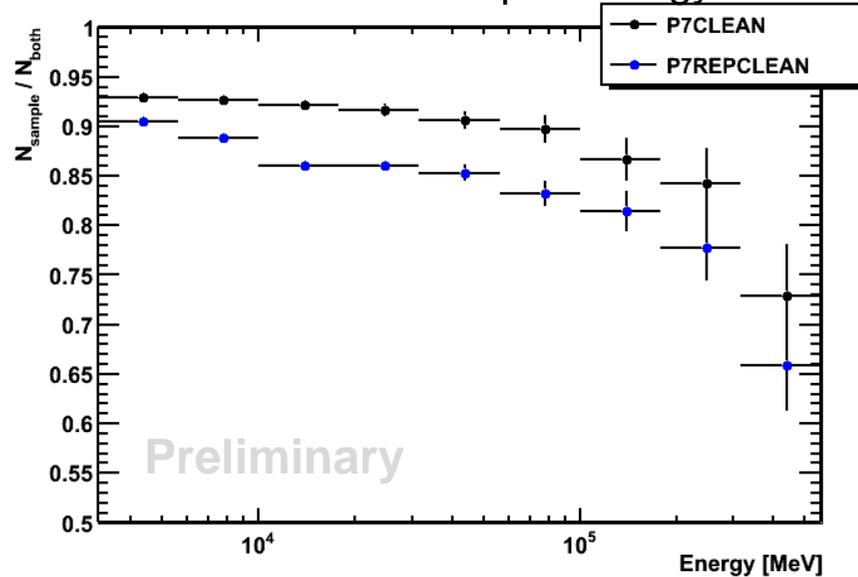
- Triggered events are dominated by CR background events
 - Need to define additional cuts to get γ -ray rich dataset
- Nested “event classes” for various types of γ ray sources
 - Transient: loosest, for flaring sources (cut in time)
 - Source: moderate, for bright sources (cut in space)
 - Clean: tight, for γ -ray diffuse
 - Ultraclean: tightest, for extragalactic γ rays

M. Ackermann et al
 (The Fermi LAT
 Collaboration)
 ApJS 203, 4 (2012)
 arXiv:1206.1896

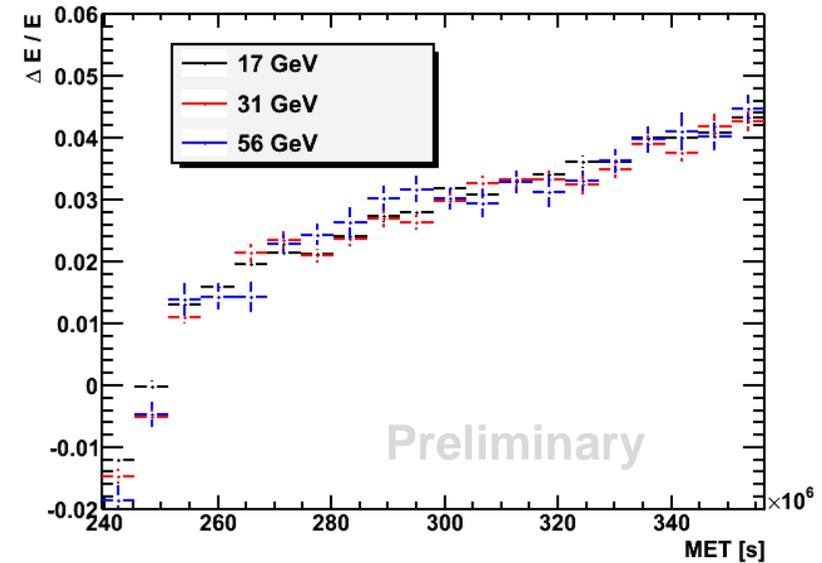




Event Overlap v. Energy

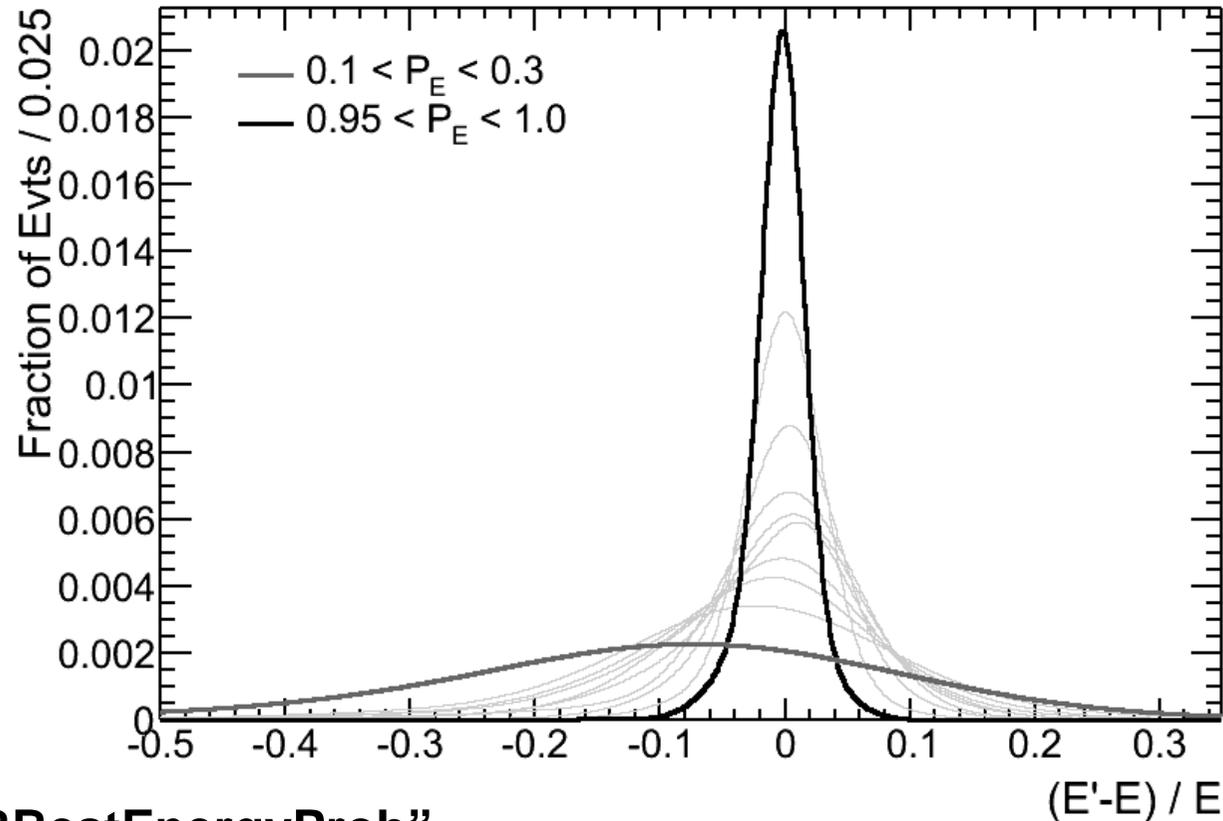


Energy Shift v. Time



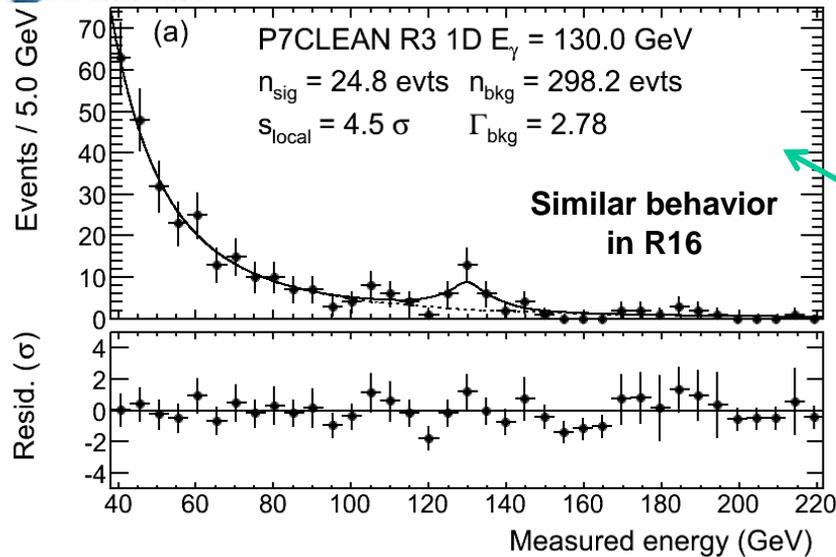
- Reprocessing Data with updated calibrations (primarily Calorimeter)
- Improves the agreement between the TKR direction and the CAL shower axis and centroid at high E, improving the direction resolution
- Corrects for loss in CAL light yield b/c of radiation damage (~4% in mission to date)
- 80%+ overlap in events between original and reprocessed samples

Energy Dispersion Model (“2D model”)

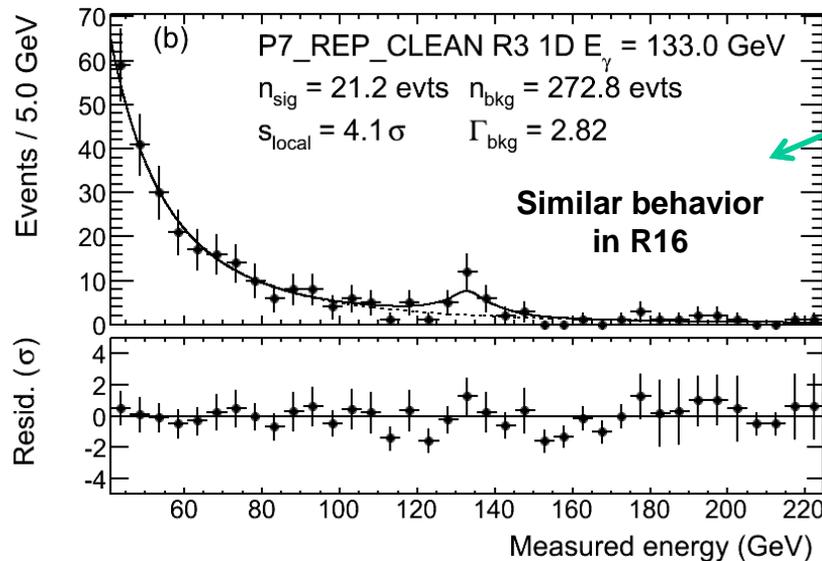


- $P_E = \text{“CTBBestEnergyProb”}$
 - Probability that the reconstructed energy is within expected 68% containment
- Use triple gaussian model in 10 P_E bins
- Gives ~15% increase in statistical power
 - Similar to adding ~30% more data

Studies of Line-like Feature near 133 GeV (1)



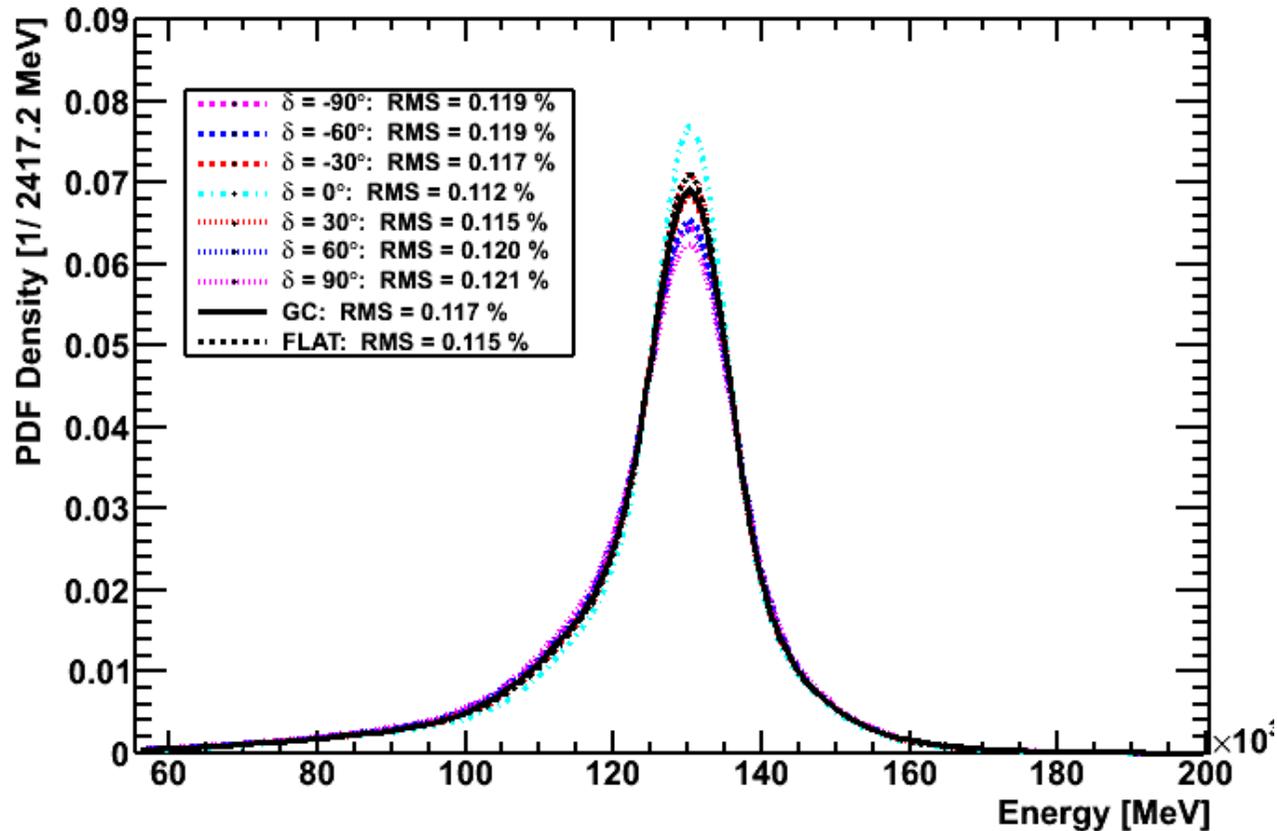
- Fits using simpler energy dispersion model
 - no use of energy recon. quality: P_E
- 4.5 σ (local) 1D fit at 130 GeV with unreprocessed data
 - Comparable to signif. reported in C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797



- 4.1 σ (local) 1D fit at 133 GeV with reprocessed data
 - Shifts higher in energy by a few percent, as expected

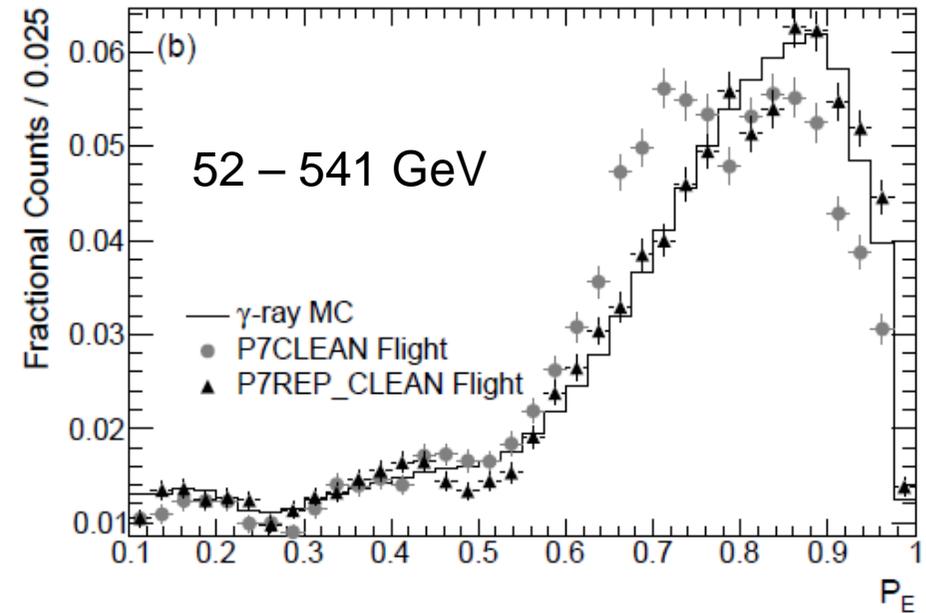
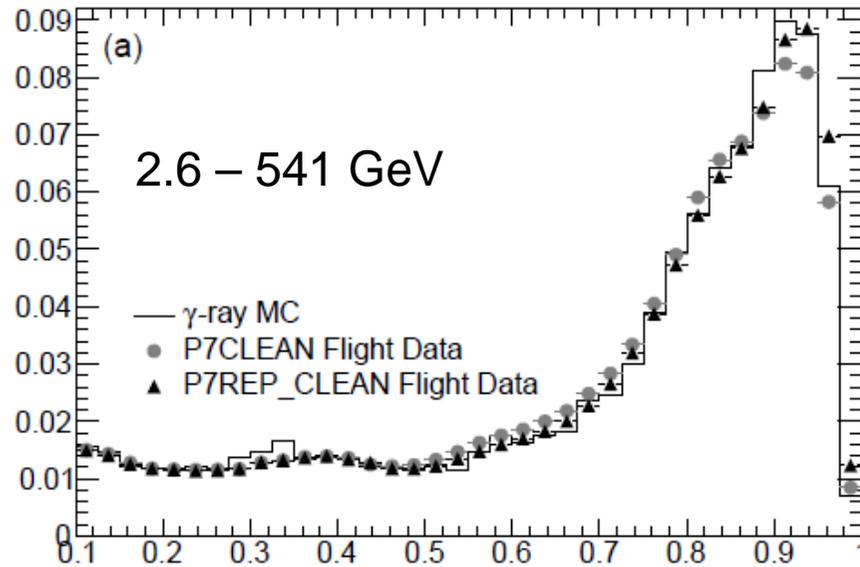


D_{eff} for Several Directions



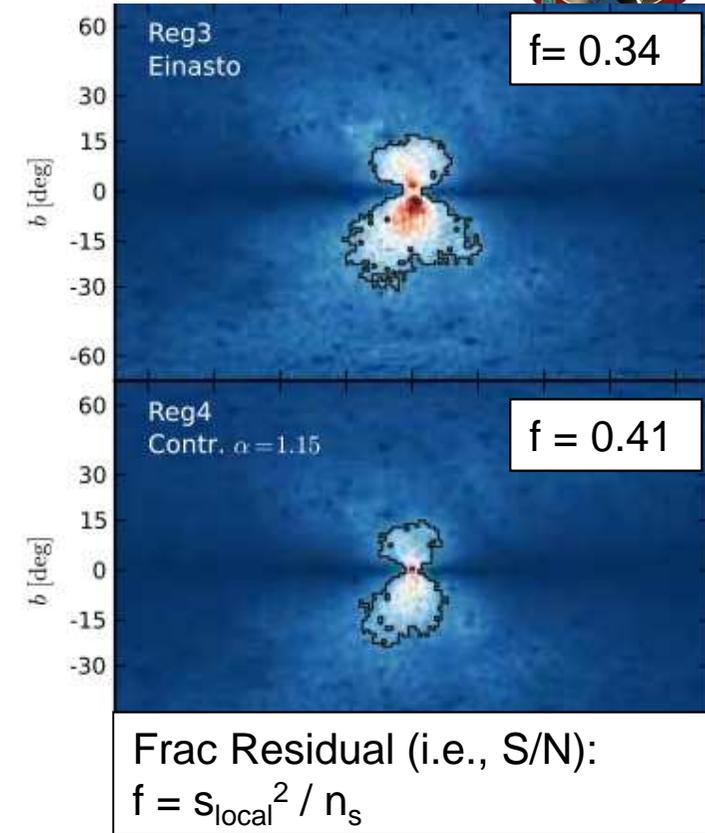
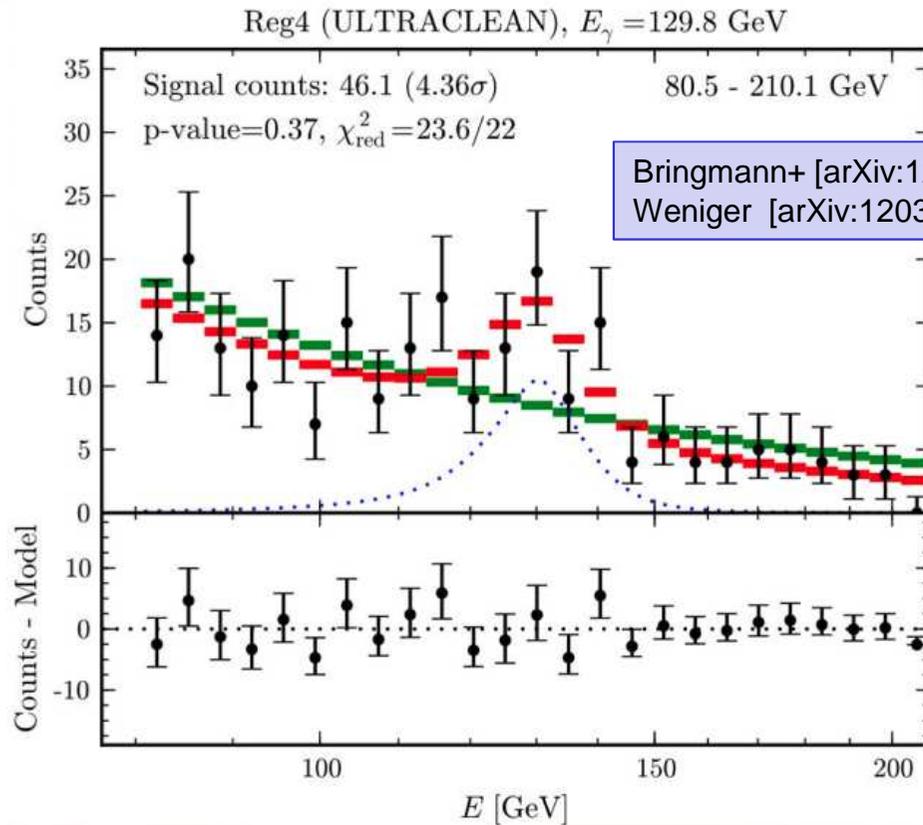
- The θ -averaged D_{eff} weighted for observing profile varies moderately with declination (δ).
- Using the wrong profile will not induce a signal, but can scale the n_{sig} and the significance of a signal by up to 25%.

P_E distribution in data vs MC



- Use “all-sky” MC with diffuse + 2FGL and full orbit history

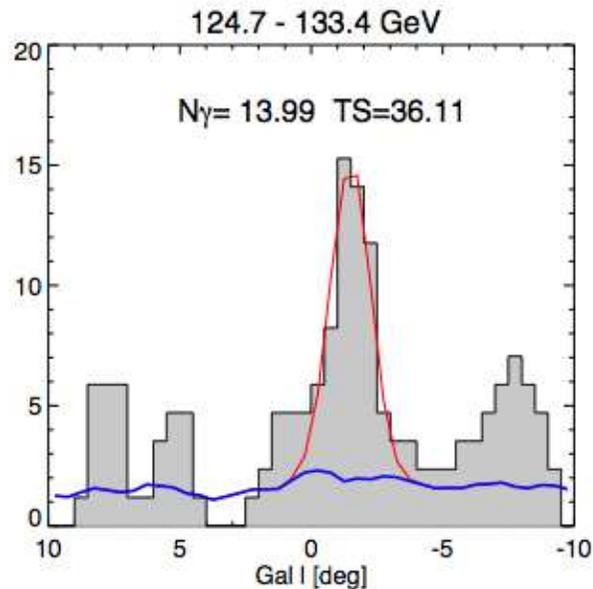
Reported Narrow Feature at 130 GeV (1)



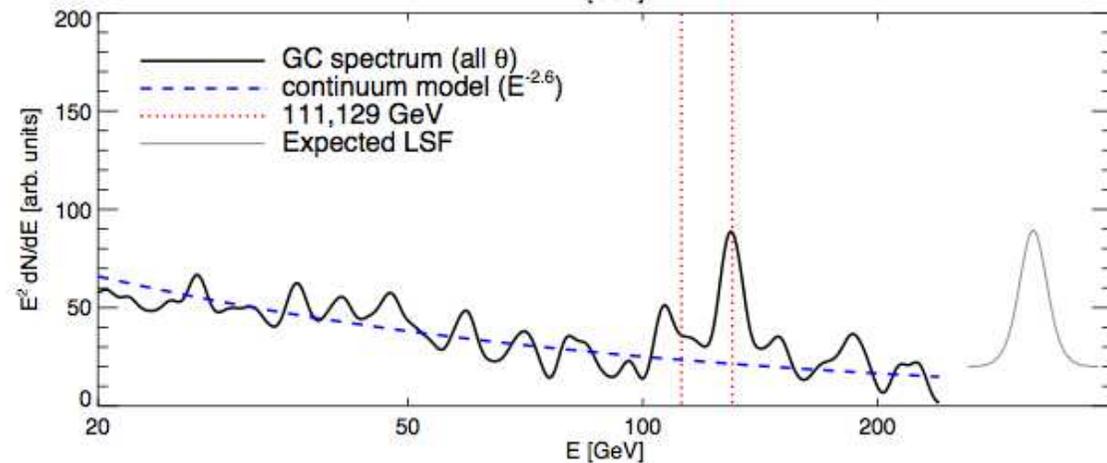
- Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC)
- Signal is particularly strong in 2 out of 5 test regions, shown above
- Over 4σ , with S/N > 30%, up to ~60% in optimized regions of interest (ROI)



Gal. Long. Profile at ~130GeV



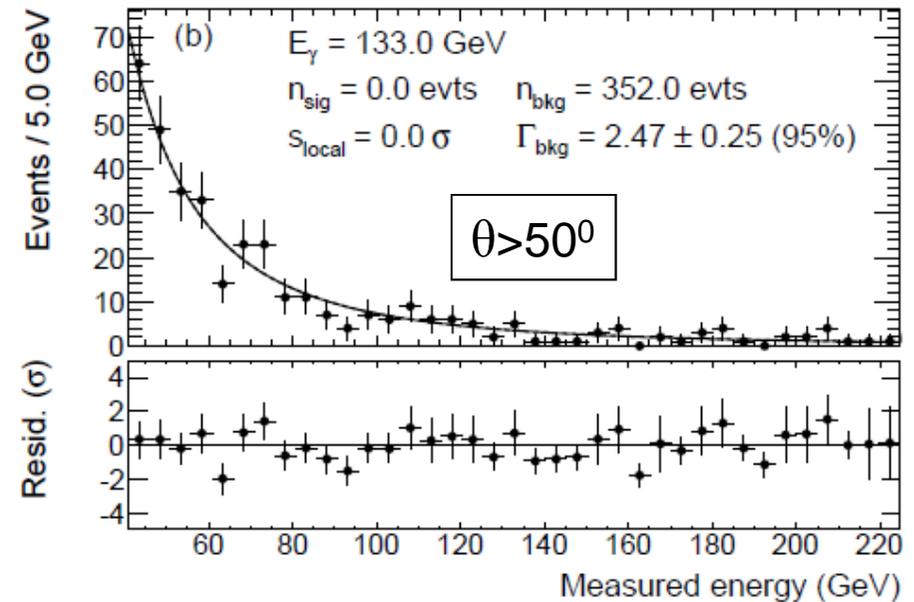
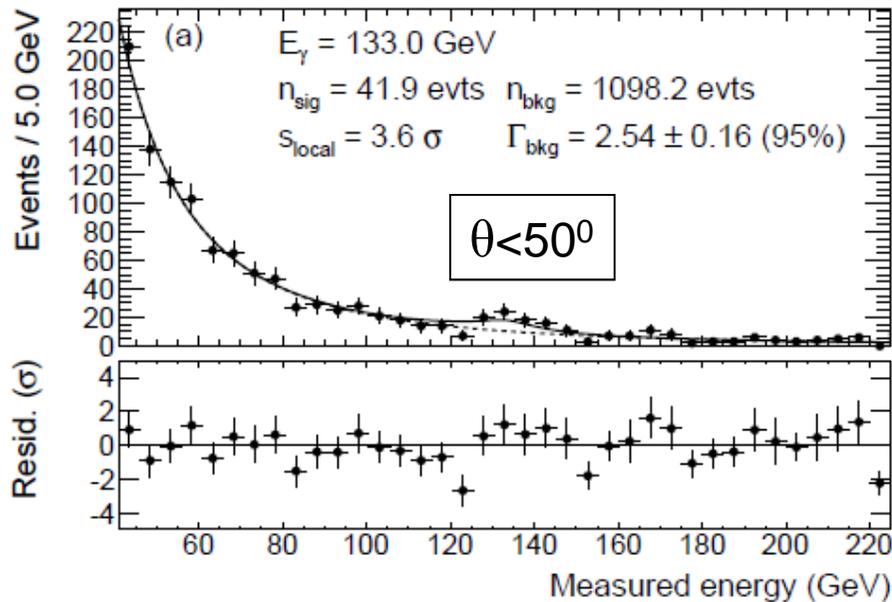
Energy Spectrum from GC



Su & Finckbeiner [arXiv:1206.1616]

- Su & Finkbeiner [arXiv:1206.1616v2] showed that the spectral feature was close to, but slightly offset from, the GC
- Likelihood analysis included the spatial morphology of signal, and a data-driven model of Galactic astrophysical backgrounds
- $\sim 5.0\sigma$ statistical significance (one line), after a trials factor of ~ 6000 , but acknowledged uncertainties of modeling the Galactic astrophysical backgrounds

θ -dependence of 135 GeV feature



- Search in a 20x20 GC box (no source removal, 2D model)
- 135 GeV feature appears in low- θ events, but not in high- θ events
 - 3.5 σ in $\theta < 50^\circ$ events should scale to 2 σ for $\theta > 50^\circ$ events
- Same behavior observed in the Limb feature